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Design of High Strength Concrete Filled Tubular Columns For Tall Buildings

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Abstract

Ultra-high strength concrete and high tensile steel are becoming very attractive materials for high-rise buildings because of the need to reduce member size and structural self-weight. However, limited test data and design guidelines are available to support the applications of high strength materials for building constructions. This paper presents significant findings from comprehensive experimental investigations on the behaviour of tubular columns in-filled with ultra-high strength concrete at ambient and elevated temperatures. A series of tests was conducted to investigate the basic mechanical properties of the high strength materials, and structural behaviour of stub columns under concentric compression, beams under moment and slender beam-columns under concentric and eccentric compression. High tensile steel with yield strength up to 780 MPa and ultra-high strength concrete with compressive cylinder strength up to 180 MPa were used to construct the test specimens. The test results were compared with the predictions using a modified Eurocode 4 approach. In addition, more than 2000 test data samples collected from literature on concrete filled steel tubes with normal and high strength materials were also analysed to formulate the design guide for implementation in practice.

Keywords: Composite structure, Concrete filled steel tube column, High tensile steel, Ultra-high strength concrete, Fire resistance

1. Introduction

The need for sustainable construction is hastened around the world aiming to reduce the consumptions of construction materials. Some ways to achieve this is to replace the conventional concrete with more sustainable non-concrete alternatives such as steel, or to use higher strength concrete. The production of ultra-high strength concrete (UH SC) with compressive strength greater than 140 MPa becomes possible with the development of concrete technology and availability of a variety of materials such as silica fume and high-range water-reducing admixtures. However, its application has been currently limited to special applications such as offshore and marine structures, industrial floors, pavements, and security barriers. In terms of steel, the production of high tensile steel with tensile strength around 800 MPa becomes possible with the development of metallurgical technology and availability of a variety of alloy elements. However, high tensile steel are mostly used in cars, trucks, cranes, bridges, roller coasters and other structures that are designed to resist abrasion and high stresses and in applications that require high strength-to-weight ratio.

High strength construction materials are now attractive owing to their economic and architectural advantages. The higher the material strength, the smaller is the required member size. Floor space can be saved and cost can be significantly reduced in high-rise construction. However, material brittleness could be one of the problems for ultra-high strength concrete and local buckling may be a problem for structural members with high tensile steel. To overcome these problems, one solution is to use composite structural members, especially concrete filled steel tubes (*CFSTs*) as columns, where the ductility and strength of the concrete core can be enhanced by the confinement effect provided by the steel tubes while the local buckling of the steel tube can be delayed or even prevented by the concrete core (Liew and Xiong, 2012). In addition, the steel tube can serve as permanent formwork for concrete casting and thus it eliminates the need for formwork and leads to fast track construction and economical design (Liew and Xiong, 2009).

However, current design codes for composite columns may be only applicable for normal strength concrete and steel. For example, Eurocode 4 applies to composite columns with normal weight concrete of strength classes C20/25 to C50/60 and steel grades S235 to S460 (EN 1994-1-1, 2004), AISC 360-10 only applies to composite columns with normal weight concrete cylinder strength from 21 MPa to 70 MPa and steel yield strength up to 525 MPa (AISC, 2010), and DBJ only applies to composite columns with normal weight concrete cylinder strength

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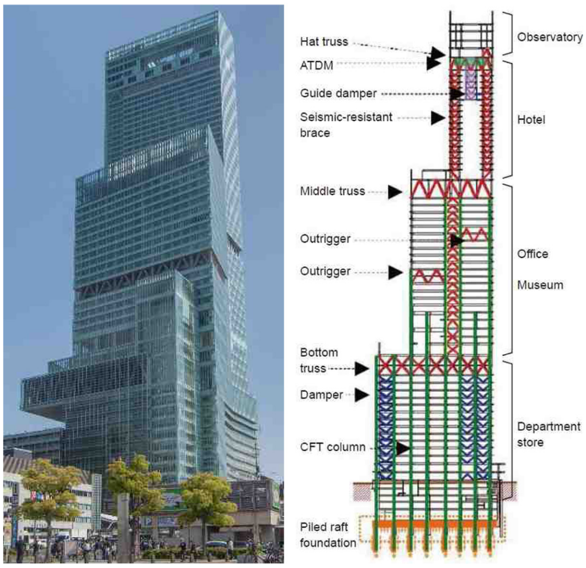
a) Obayashi Technical Research Institute Main Building (Tokyo, f_y=780MPa and f_{ck}=160MPa for *CFST* columns)

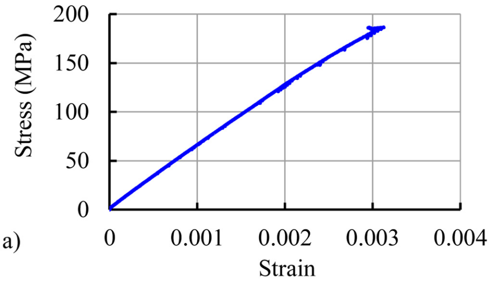


b) Abeno Harukas (Osaka, f_y=590MPa and f_{ck}=150MPa for *CFST* columns)

Figure 1. Building constructions using high strength concrete and steel in *CFST* columns.

from 25 MPa to 65 MPa and steel yield strength from 235 MPa to 430 MPa (DBJ, 2010). Therefore, more work should be done to extend current design codes or propose new provisions for composite columns with high strength materials.

In this paper, significant findings from comprehensive experimental studies on the behaviour of tubular columns in-filled with ultra-high strength concrete at ambient and elevated temperatures are presented. Ultra-high strength concrete of compressive strength up to 180 MPa and high tensile steel of S700 were used in the composite columns. Both single-tube and double-tube sections were studied. Ultimate resistances obtained from tests are compared with the predictions by modified Eurocode 4 approach. Database of tests on CFST columns in literature is established to guide for future work on the applications of high strength materials.



a)

b) Plain UHSC SF+UHSC UHSC+CA

Figure 2. a) Uniaxial stress-strain curve of *UHSC* under compression; b) failure modes of various UHSC mixtures.

Figure 3. Spalling of *UHSC* at high temperature.

2. Material Characteristics

2.1. Ultra-high strength concrete

UHSC is very brittle under compression, and the uniaxial stress-strain curve is almost a straight line as shown in Fig. 2(a). Once cracked, the *UHSC* cylinders were instantly crushed into pieces and there is no post peak ductility and thus descending part of the stress-strain curve could not be obtained. The Poisson's ratio is about 0.23 and the modulus of elasticity is about 63 GPa.

Ductility of *UHSC* could be improved by adding steel fibres (SF) or coarse aggregates (CA) as shown in Fig. 2. b). The ductility is improved but the descending parts of the stress-strain curves still cannot be measured in tests even the SF and CA are added.

UHSC is prone to spall at high temperatures as shown in Fig. 3. The spalling is caused by thermal stress due to temperature gradient during heating, and the splitting force by release of vapor water around 100°C. It has been established by tests that polypropylene fibre with content of 0.1% is effective to prevent the spalling of *UHSC* since the vapor pressure can be released through the voids left by melted polypropylene fibres at approximately 170°C.

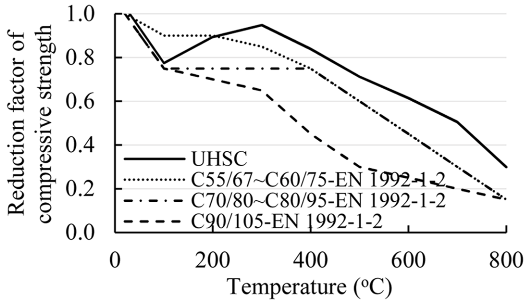


Figure 4. Normalized compressive strength of different grades of concrete at elevated temperatures.

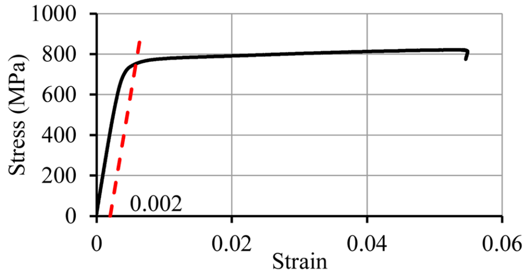


Figure 5. Uniaxial stress-strain relationship for high tensile steel.

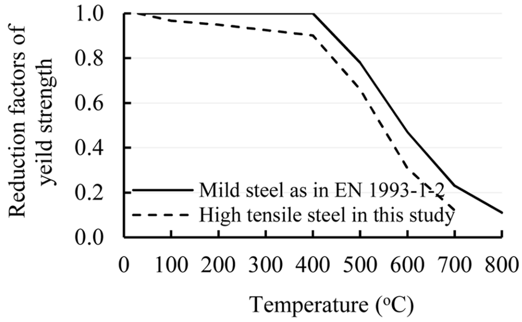


Figure 6. Normalized yield strength of mild and high tensile steel at elevated temperatures.

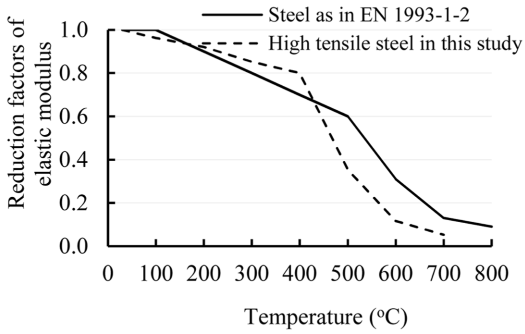


Figure 7. Normalized elastic moduli of mild and high tensile steel at elevated temperatures.

In practice, the hollow steel section shall contain holes with a diameter of not less than 20 mm located at the top and bottom of the *CFST* column in every storey to release the vapour in the concrete caused by fire.

The present UHSC exhibited better fire performance in terms of temperature-dependent strength compared with high strength concrete (HSC). The comparison between strength reduction factors of *UHSC* and *HSC* as in EN 1992-1-2 are shown in Fig. 4. It can be seen that, beyond 200°C, the reduction factors of *UHSC* are higher than those of *HSC*, indicating slower reduced strength in fire. The reason is attributed to bauxite aggregates used in *UH SC*, which are normally used for refractory concrete to improve heat resistance of concrete compared with NSC and HSC with traditional siliceous or calcareous aggregates.

2.2. High tensile steel

The high strength steel plates that were used in the test specimens is a product of Corus, RQT 701 steel. The uniaxial stress-strain relationship for the high tensile steel obtained from the coupon tests is shown in Fig. 5. Different from mild steels, there is no significant yielding plateau or hardening effect. Under tension, the maximum elongation is much smaller, sudden fracture may occur, and no significant necking deformation is developed. Therefore, high strength steel is not as ductile as mild steel. The 0.2% proof stress is taken as the yield strength which is about 780 MPa. The Poisson's ratio is about 0.3, and the modulus of elasticity is about 200 GPa.

Investigation was also carried out on High strength steel subject to elevated temperature in order to obtain their temperature mechanical properties in fire situation. Both steady and transient test methods were adopted to measure yield strength at high temperatures as shown as shown in Fig. 6. The results are compared with the reduction values recommended in Eurocode 3 for mild steels. It is found that the high tensile steel exhibited faster reduced yield strength than mild steels when subject to fire. Fig. 7 gives the temperature-dependent elastic moduli which were reduced faster beyond 400°C due to effects of creep. The investigation on mechanical properties indicates that more fire protection materials may be needed for the high strength steel members.

3. Structural Behaviour at Ambient Temperature

For the study on structural behaviour of tubular columns infilled with *UHSC*, tests were carried out on stub columns under concentric compression, beams under bending, and slender beam-columns under concentric and eccentric compression. For stub column tests, there were 35 circular specimens with mild steel, 5 square specimens with

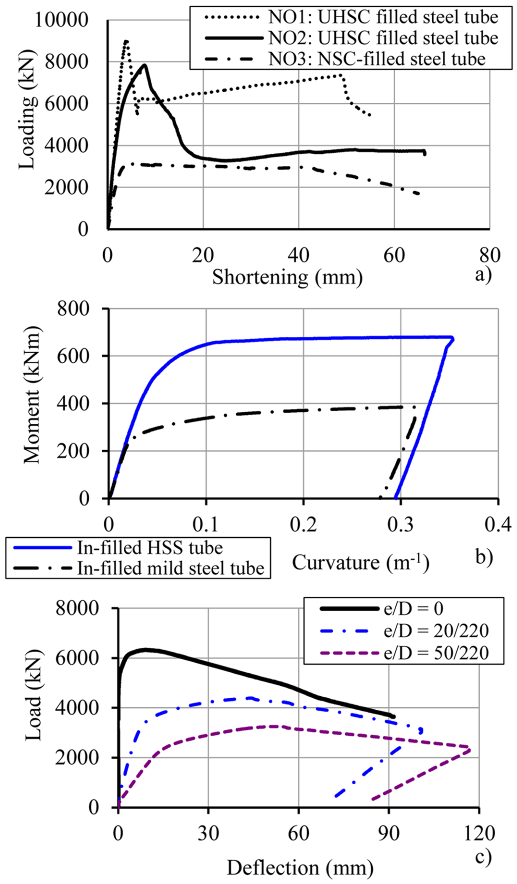


Figure 8. a) Stub columns; b) Beams; c) Slender beam-columns.

mild steel, and 16 square specimens with high tensile steel. For beam tests, there were 3 circular specimens with mild steel, 1 square specimen with mild steel, and 4 square specimens with high tensile steel. For concentrically and eccentrically loaded slender beam-column specimen tests with L/D ratio ranging from 18 to 20, there were 9 circular specimens with mild steel, 1 square specimen with mild steel, and 4 square specimens with high tensile steel. Typical loading curves are shown in Fig. 8.

3.1. Ductility

Structures and members are usually required to have sufficient ductility so that serviceability requirements can be satisfied even undergoing significant deformations. Due to the brittleness of *UHSC*, tubular columns in-filled with *UHSC* may also behave in brittleness.

For stub columns, Fig. 8(a) shows typical loading-shortening curves of two *UHSC* filled steel tube specimens, compared with one normal strength concrete (*NSC*) filled steel tube specimen. The steel contribution ratio of Specimen NO1 was 0.40, higher than that of Specimen NO2 which was 0.23, close to the lower limit value of 0.2 as recommended in Eurocode 4. Due to the brittleness of the *UHSC* core, very loud cracking/crushing noise was heard around the first peak load during the testing for most of the *UHSC* filled steel tube specimens. A steep drop in the loading-shortening curves was observed right after the peak load. Soon after the load drop, visual inspection was carried out on the specimens and no visible deformation was observed. Therefore, the noise was thought to be originated from the crushing of the *UHSC* core. For Specimen NO1 with higher steel contribution ratio, the second peak load is about an 70% of the first peak load. For Specimen 2 with lower steel contribution ratio, the second peak load is about 50% of the first peak load. The second peak load herein is defined as residual resistance. To meet requirements of ductility, the residual resistance should not be less than the actions under serviceability limit state. For gravity load combination, the service load is up to 70% of the ultimate resistance according to the partial factors for actions and materials used in Eurocode 4. Therefore, to ensure a safe design, the residual resistance should be at least equal to 70% of the designed ultimate resistance. Therefore, the lower limit of steel contribution ratio as recommended in Eurocode 4 should be increased. Based on the test results, it is recommended that the limit should be increased from 0.2 up to 0.3. For the *NSC* filled steel tube specimen, sufficient ductility was ensured in post-buckling.

Different from brittle behaviour observed from stub column tests, very ductile behaviour was observed from beam specimen tests as shown in Fig. 8(b) for two *UHSC* filled steel tubes. For slender beam-columns, typical load-lateral deflection curves are shown in Fig. 8(c) for three specimens with different values of eccentricity. The load-deflection curves after reaching the peak load were also recorded and the results indicated that strength degradation was gradual without brittle or sudden failure, especially for specimens with larger value of eccentricity.

3.2. Confinement effect

For *UHSC* filled tubular columns, the concrete core under compression was crushed before the steel yielded and in the elastic range of the load displacement curve, the Poisson's ratio of UHSC is smaller than that of steel. As

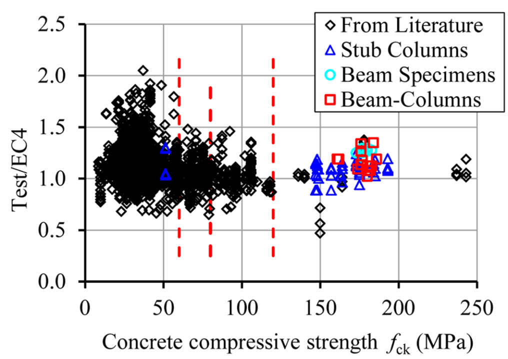


Figure 9. Test data showing the ratio of test to Eurocode 4 prediction with concrete strength.

a result, no significant confinement effect could be developed until the first peak load was reached. Therefore, confinement effect should not be considered for *UHSC* filled steel tubes.

Fig. 8 shows the test to EC4 prediction ratios based on 2019 test data collected from the literature together with specimens from the authors' tests on tubular members infilled with ultra high strength cementitious grouts. It can be seen that Eurocode 4 provides conservative predictions for all the beam and beam-column specimens, and for most of the stub column specimens. Test data has been extended to cover ultra high strength concrete with compressive strength up to 180 MPa but more test data are needed for concrete filled tubes with concrete strength between 120 MPa and 150 MPa.

4. Structural Behaviour under Fire

A total of 22 *CFST* specimens with *UHSC* and high strength steel were tested under ISO-834 fire. The investigated parameters are the profiles of cross-section (circular and square), single-tube, double-tube, cross-sectional size, thickness of steel tube, strength of steel, load level, boundary condition, eccentricity of load and thickness of fire protection material. The hot-rolled steel S355 was used for all circular columns. All square column sections were pre-fabricated by welding four high strength steel plates at the corners. In order to make sure the column is loaded and supported outside the furnace, all columns were designed to be 3.81 meter long including the thickness of end plates. In addition, the cross-sectional sizes of all columns were around 200~300 mm. The concrete was pumped into tubes from the bottom of the columns using grouting pipes with 0.1% polypropylene fiber by volume to prevent spalling in fire. The fire protection material was a mixture of Portland cement, perlite, vermiculite and water. The fire protection material was applied by scraper after the columns was primed. Eight circular steaming holes with diameter of 10 mm were provided on each column to release the vapor inside the concrete during heating.

The tested columns are shown in Fig. 10. It was observed during testing that no spalling occurred. The noise of crack was not heard as for testing at ambient termperature. Fire protection material spalled for most columns in tests. Most columns were failed by overall buckling except 3 columns failed by inadequate cross-sectional capacity.

Welding tearing failure was found on one square *CFST* column with high strength steel as shown in Fig. 11. The weld tearing was caused by the concrete expansion force which was transverse to the welds. As a result, the welds were subjected to transverse tension at elevated temperatures. However, the weld failure was not found on other welded high strength steel box columns infilled with UHSC. This is because the failure temperatures of the said columns was lower than that of column with tearing failure. Hence, the weld strengths of the said columns was reduced less and not failed. Nevertheless, the weld failure of welded box section with high strength steel under fire can be effectively prevented by ensuring good

Figure 10. Failure modes of *CFST* columns with ultra-high strength concrete and high strength steel under fire.

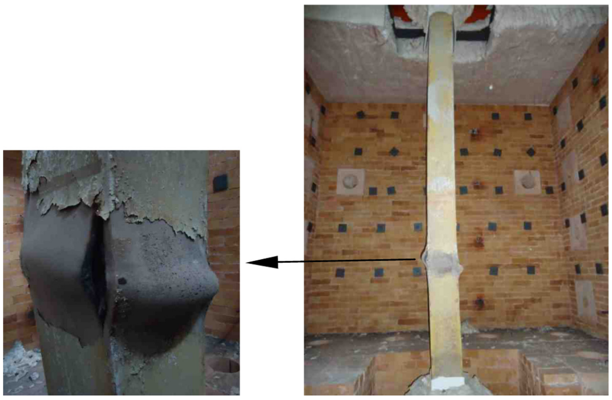


Figure 11. Weld tearing of welded box section with HTS.

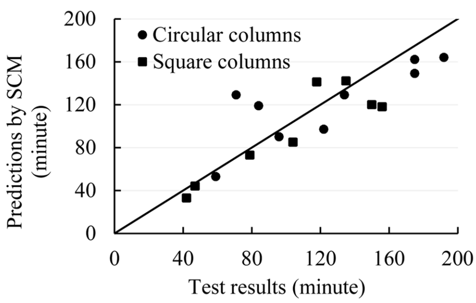


Figure 12. Predictions by simple calculation model in EN 1993-1-2.

weld quality with the use of matching electrodes, such as low-hydrogen electrodes. The welds failure indicated premature failure under compression.

The tested fire resistance time was compared with predictions by simple calculation method (SCM) in EN 1993-1-2 (2005) as shown in Fig. 12. *SCM* is only applicable for columns subject to axial load. It can be seen that for most columns the test results were greater than the predictions, indicating conservative design by EN 1993-1-2. The average value and standard deviation are 1.114 and 0.229, respectively. Overall, the simple calculation method could be used to determine the fire resistance of CFST columns with high strength materials.

5. Test Database

1819 test results on both circular and rectangular CFST columns have been reported by Goode (2008). This paper expands the database of Goode to include 2019 test results on CFST columns based on the research work done in NUS (Liew et al., 2013). The new test data include recent research on steel tubes infilled with high strength concrete. The test results are compared with the resistance predicted by EC4 (EN 1994-1-1, 2004). This database includes short and long CFSTs subjected to compression, uniaxial bending, and bi-axial bending. Tests on encased columns, columns with stainless and aluminium steel sections are excluded. Results from tests involving preload effect, sustained loading for creep and shrinkage studies and dynamic loadings are not included. In addition, CFST columns with Class 4 slender sections, in which the d/t ratio exceeds the class 4 limit stipulated in EN 1994-1-1, are also excluded although they were included originally in Goode's database. The test results by the authors are included in this database.

The comparison between test results and the predictions by EC4 as shown in Fig. 13 which shows limited experimental investigations on *CFSTs* with high-strength materials. 79.8% of the test data have a concrete strength less than 60 MPa, 10.8% have a concrete strength in the range of 60 MPa to 90 MPa and only 9.4% have a concrete strength higher than 90 MPa. For steel, only 8.3% test data have a steel yield strength higher than 460 MPa. Hence most of the tests concentrate on normal strength materials and there are significant gaps in the range of high-strength concrete (f_{ck}>60 MPa) and high tensile steel (f_y>460 MPa). Since high strength materials become more and more attractive for high-rise construction. More research effect should be put on their applications for which current design codes should be extended.

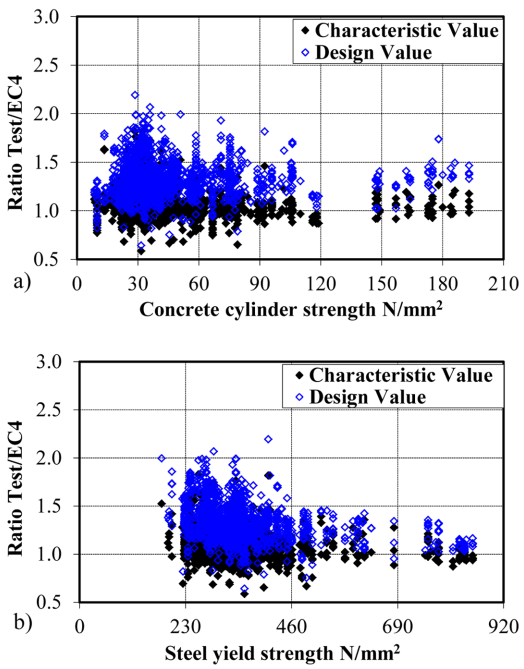


Figure 13. Tests on *CFSTs* with different a) concrete and b) steel strengths.

6. Conclusions

Design considerations on use of high strength materials in *CFST* columns are discussed in this paper based on the authors' findings from experimental work.

- Failure of stub *UHSC* filled steel tube columns with low steel contribution ratio under compression may be very brittle. The lower limit of steel contribution ratio as recommended in Eurocode 4 should be increased from 0.2 to 0.3;
- For tubular columns employing *UHSC*, confinement effect should be ignored;
- The overall behaviour of *UHSC* filled steel tubes under bending is very ductile. Full plastic moment resistance can be achieved;
- Explosive spalling may be a critical problem for *UH SC* at high temperature. polypropylene fibres can be added to overcome this problem;
- At high temperature, strength reduction is less for for *UHSC* than normal strength concrete, while more strength reduction is expected for high tensile steel compared (S700) to mild steel (S275 and S355);
- Eurocode 4 limitation on concrete strength could be further extended to C180 concrete and high tensile steel S700 for both room temperature and fire resistance design, according to the recent tests done by the authors. Further analysis of the test database indicates that more research work should be carried out for concrete filled tubular members with concrete grade between C120 and C150.

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